CdTe Back Contact: Response to Copper Addition and Out-Diffusion

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ABSTRACT

The back-contact barrier of CdTe solar cells plays an important role in cell operation, and it is substantially altered by both the amount of copper used in forming the contact and the movement of copper away from the contact during elevated temperature stress. It is shown that a simple model can explain the differences in current-voltage curves, cell uniformity, and capacitance as copper is added or moved out of the contact region, as well as the dependence of copper movement on electrical bias.

1. Back-Contact Model

The use of copper to make improved contact to thin-film CdTe for solar cell applications is well established [1]. Since the CdTe used in solar cells is a relatively wide band-gap p-type semiconductor, a metallic contact can form a large Schottky barrier for holes that may seriously limit current flow. In a circuit model, the back contact forms a diode of opposite polarity to the primary junction [2], which distorts the current-voltage (J-V) curves in a manner often referred to as the "rollover" effect. Copper can either form a distinct copper telluride layer or it can dope the CdTe more heavily in the p-direction. In either case, the addition of copper will progressively lower the back-contact barrier that holes see and lead to the solid band profiles illustrated schematically in Fig. 1. Conversely, removal of copper from the back-contact region will increase the back-barrier height and progressively limit current flow as illustrated by the dashed band profiles.

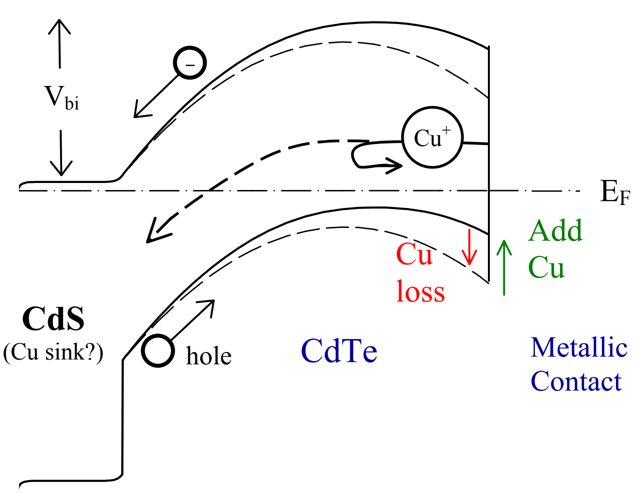

Figure 1. CdTe solar-cell band diagram showing possible effects due to variation in back-contact copper.

An additional feature to note in Fig. 1 is how the primary-junction field might influence the movement of copper. Cu is well known to be a fast diffuser, and especially since polycrystalline CdTe is relatively porous, the Cu could very easily move into or through the CdTe layer leaving little in the back contact region. Assuming that it is a positive ion, however, the junction field of the cell will resist the forward diffusion. Hence, the rate of diffusion would be expected to be dependent on the bias across the cell. This point is illustrated in Fig. 2, which shows efficiency changes in CdTe cells made by First Solar, Inc. that were held at 100°C for 20 days. Both under illumination and in the dark, the change in efficiency becomes significantly larger in forward bias when the junction field is reduced. The abbreviations are SC for short-circuit, MP for maximum power, and OC for open-circuit. The light and dark voltages shown were adjusted to be the same.

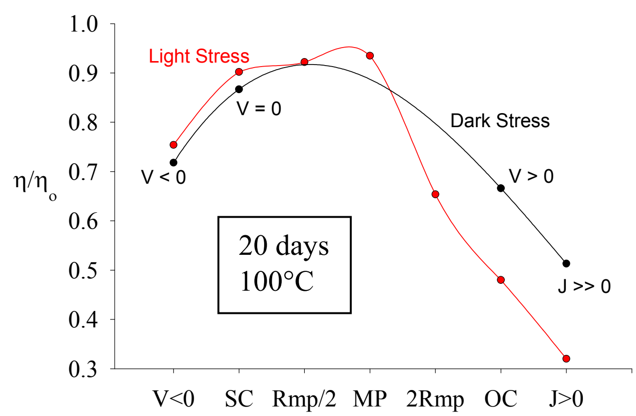

Figure 2. Efficiency changes as a function of bias during elevated-temperature stress [from Ref. 3].

The efficiency reductions shown in Fig. 2 were mainly due to current limitations resulting from the barrier. However, another point illustrated by Fig. 1 is that when there is significant band bending at the back contact of a cell that is depleted through much of its width, the height of the primary junction is limited, and hence the built-in potential V_{bi} available is reduced. The practical result of such an interaction between the two junctions can be a reduction in the photovoltage of the solar cell [4].

2. J-V Variations

Figure 3(a) illustrates the typical variations seen in the CdTe current-voltage (J-V) curves when the amount of copper used in the back contact is varied. The cells shown were fabricated by W. Sampath's group at Colorado State, and correspond sequentially to no intentional copper, ¼ the standard amount used, ½, 1 and 2 times. The standard amount is roughly equivalent to 2 nm. Without intentional copper (black dots), the curve is significantly washed out in the power quadrant and is current limited for positive current. There are progressive improvements up to the normal amount, but additional copper makes little difference.

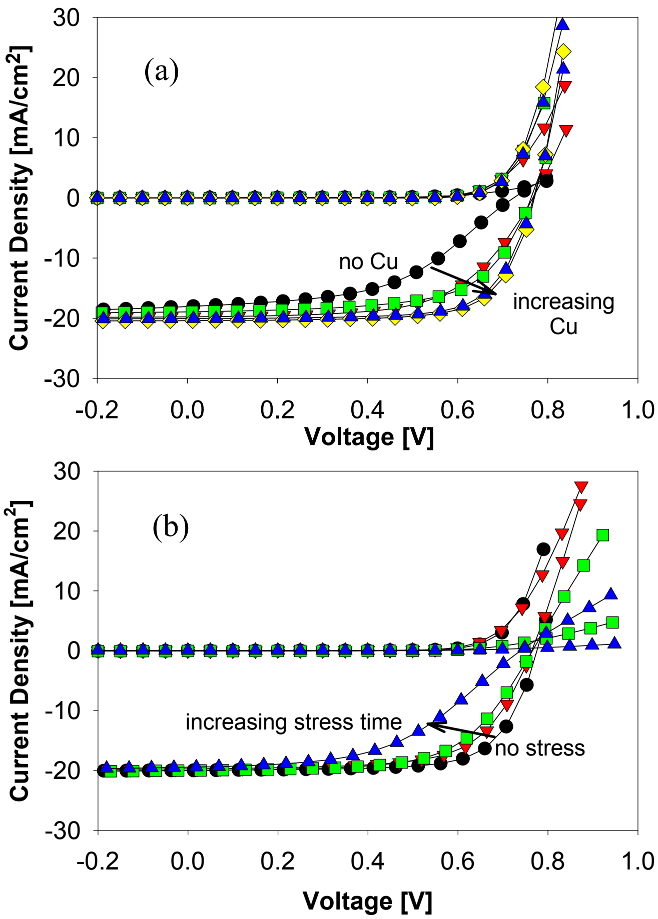

Figure 3. Variations in J-V curves with (a) amount of copper concentration and (b) stress time [from Ref. 5].

Figure 3(b) shows a highly suggestive reversal of the progression in Fig. 3(a) when a cell with a standard amount of copper is stressed under illumination at short-circuit and elevated temperature (100°C) for increasing lengths of time. In this case the black dots are for the as-deposited cell and the other curves correspond to stress times of 8 hrs, 8 days, and 24 days. At the two latter times, the current limitation, or "rollover", has clearly returned.

3. Uniformity Variations

Figure 3 makes the argument that diffusion of copper away from the junction affects the barrier shown in Fig. 1 in the opposite direction as adding copper and does nothing else of significance. This argument is reinforced by an examination of the uniformity of the cells, which was done with a small-spot measurement apparatus that utilizes focused diode lasers with intensity at the cell adjusted to approximately one sun [6]. Fig. 4 shows photocurrent maps (expressed as the quantum efficiency at 638 nm) of two cells: Fig. 4(a) is from a cell fabricated with no intentional copper at the back contact, and Fig. 4(b) is from a cell with the smallest intentional amount (1/4 the standard). The cell made without Cu shows both a substantial current variation across the cell and local areas of additional current reduction. When the light spot used as a probe is focused to a smaller diameter, these areas become more pronounced. In contrast, the cells made with back-contact copper, even a small amount, show a very uniform response, as seen in Fig 4(b).

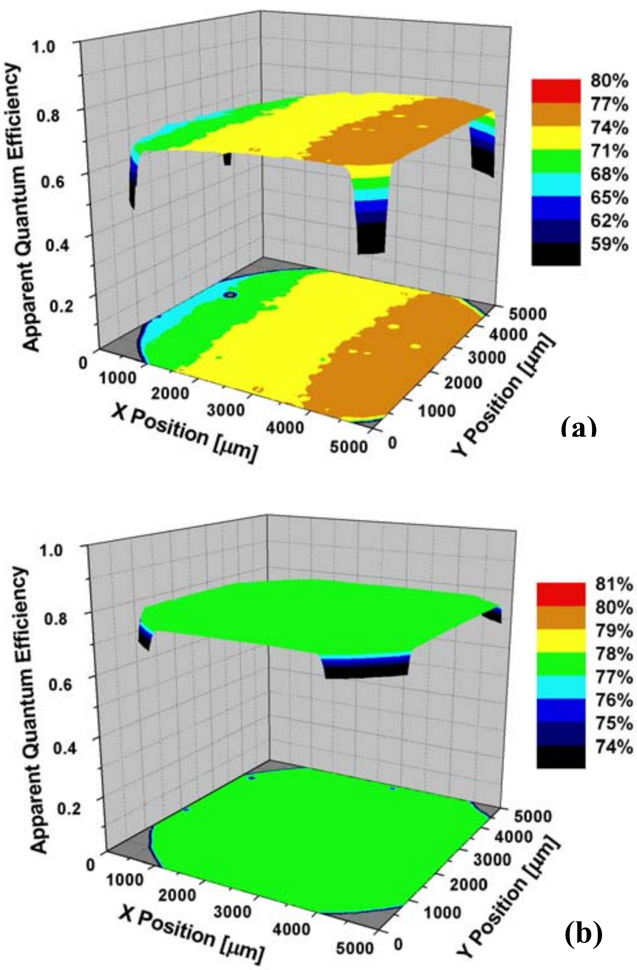

Figure 4. Contrasting uniformity of cells made (a) without Cu and (b) with a small amount in the back contact.

When the uniform cell from Fig. 4 was subjected to elevated-temperature stress (100°C for 2 days at open circuit and under illumination), its quantum efficiency became considerably less uniform, as illustrated in Fig. 5. As with the cells that had no intentional copper, there was a substantial current variation across the cell and local areas of additional reduction.

With more pronounced stress, we have sometimes observed large areas of a cell where the photocurrent is reduced to near zero. Our interpretation is that contact to the cell is effectively lost in these regions. Since we do have at least some contact for the initial “no Cu” cells, we assume that they contain some unintentional copper, which is consistent with normal contaminants in the materials used. We also note that even when contact appeared to be lost in local regions, there was no evidence of mechanical separation.

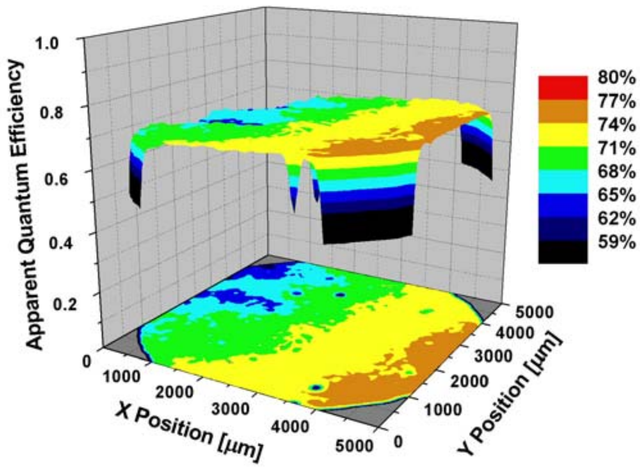

Figure 5. Reduced uniformity after elevated-temperature stress. Same cell as shown in Fig. 4(b).

4. C-V Variations

The capacitance of CdTe solar cells also varies with the amount of copper used in back-contact fabrication. Figure 6 shows the typical progression for the same cells used in Figs. 4 and 5. Prior to measuring the capacitance of each cell as a function of voltage (C-V), the capacitance vs. frequency was measured to assure that there was not significant frequency dispersion present and to choose an appropriate frequency for C-V. Figure 6 plots the capacitance data in the C^{-2}-V format commonly used to deduce carrier density. This format also allows us to plot the depletion thickness, which is proportional to C^{-1}.

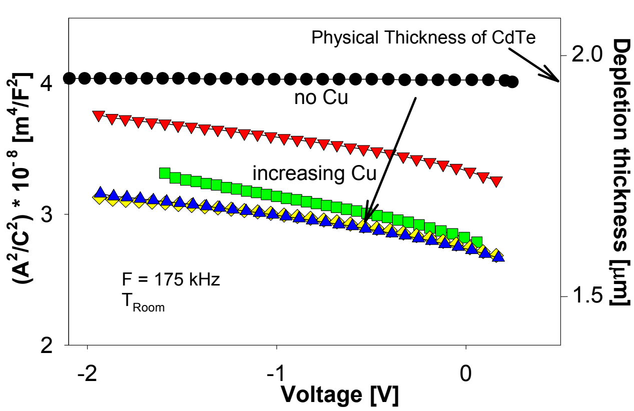

Figure 6. Variations in cell capacitance with different amounts of Cu.

Without intentional copper, the capacitance of the cell was independent of voltage and has a value corresponding to complete depletion. As copper was added, the region near the back of the cell is no longer fully depleted, suggesting physically that Cu intermixing increased the carrier density in this region. Three curves from Fig. 6 are replotted in Fig. 7 as hole density vs. position to illustrate the point. In each case there is transition from the 10^{14} range in the bulk of the CdTe to something much larger in the contact itself. Without intentional copper (black circles), the transition is very abrupt, but with ¼ (red triangles) and full (blue dots) standard copper, it becomes less abrupt corresponding to the Cu-doping of the rear part of the CdTe layer.

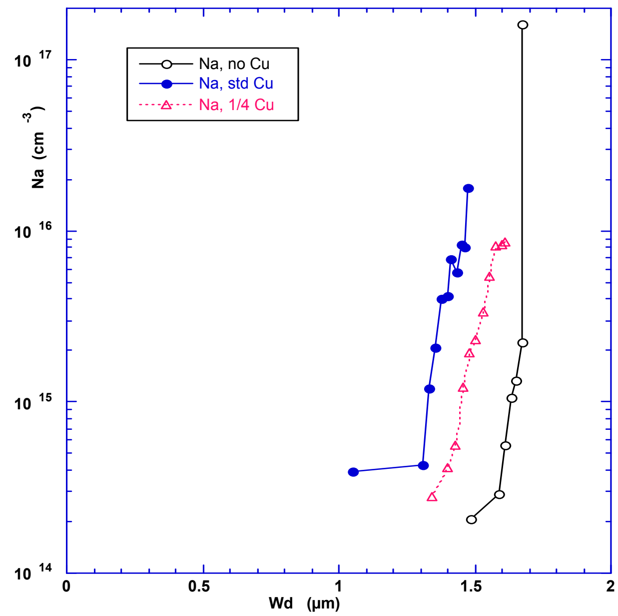

Figure 7. Three curves from Fig. 6 replotted as carrier density N_a vs. position in the CdTe.

The response of capacitance to elevated-temperature stress, as with J-V and uniformity, is highly suggestive of a reversal of copper addition. Figure 8 shows that cells with the smaller amounts of copper (1/4 and 1/2 the standard) revert to flat C-V curves very similar to those of the as-deposited cells with no intentional copper. Again the physical interpretation is that much of the copper has moved away from the back-contact region.

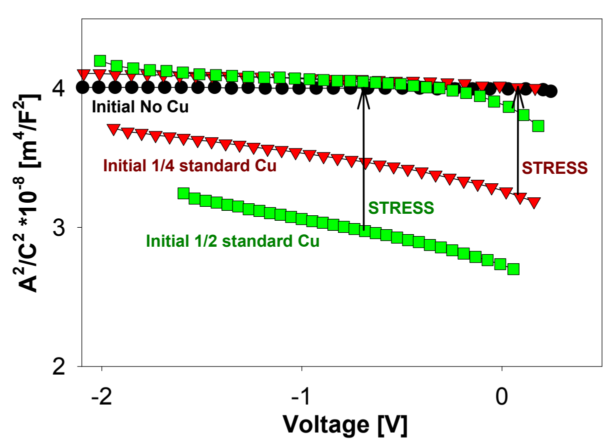

Figure 8. Flattening of capacitance curves with elevated-temperature stress.

5. Discussion

The copper model presented is by no means complete, and several points are not addressed in this paper: the possible effects of copper impurities in the CdTe layers, the reason for the downturn seen in Fig. 2 for reverse biases, and any details of the voltage loss alluded to in Section 1. Nevertheless, the copper model is both intuitively appealing and reasonably consistent with a large body of observed data. The implications of the model are fairly obvious: make sure there is sufficient copper in the contact initially and try to design and operate the cell so that the impact of copper diffusion is minimal. Strategies to achieve the latter would include the use of low porosity CdTe, relatively thick CdTe, and avoidance of periods of time at open-circuit voltage or unnecessarily high temperatures.

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